Design of a Large Pupil Relief Broadband Collimator for use in a MMW/IR HWIL Facility

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ABSTRACT

Optical Sciences Corporation has designed and implemented a 116 inch exit pupil relief optical system for dynamic infrared scene projection to flight table mounted seekers at the U.S. Army Missile Command (AMCOM) Research, Development, and Engineering Center (RDEC). The optical system collimates the output from a 512x512 element resistor array in the 3- 5µm waveband. The large pupil stand-off is necessary to support projector operation in a millimeter wave (MMW) anechoic chamber. The facility is designed to stimulate a common aperture, dual-band seeker with millimeter wave and IR imagery via a dichroic beam combiner. The dichroic beam combiner is located in the anechoic chamber and reflects the IR scene while transmitting MMW signals. The optical system exhibits distortion of less than 0.5% over the full field of view and chromatic focal shift of less than 10% of the diffraction limited range. The performance of the system is limited by the diffraction limit. This document describes the simulation environment and arrangement, outlines the design procedure from predesign and achromatization to final tolerancing, and presents final test data and sample imagery.

Keywords: Infrared, Scene Projection, Simulation, FPA Testing, Hardware- in- Loop, Optical Design, Collimator.

1.0 OVERVIEW

1.1 Dual-band Testing Requirement

Some of the latest seeker designs utilize a common aperture millimeter wave (MMW) radar and imaging IR (IIR) sensor. The sensor is capable of detecting and homing on targets using both the MMW radar and the broadband IIR sensor simultaneously. The dual-band sensor provides the seeker with an all-weather, autonomous, hit-to-kill capability for many types of targets.

The AMCOM Advanced Simulation Center (ASC), located within the RDEC, provides HWIL simulation support to tactical precision guided missile and submunition programs for the U.S. Army, DoD agencies, NATO members, and other U.S. allies.[1] As such, the ASC requires the capability for stimulating common aperture dual-band sensors. Common aperture testing is made possible at AMCOM through the use of a dual-band combiner capable of transmitting MMW while at the same time reflecting broadband IR radiation. In the MMW environment, antennae located at the opposite end of the chamber are used as radiation sources while, for the IR, a Honeywell resistor array based IR scene projector generates dynamic scenes. The Honeywell resistor array currently being used is called the Bright Resistive Infrared Thermal Emitter I (BRITE I).

1.2 BRITE Description

The BRITE I is one of several dynamic IR scene projector technologies currently being applied at the AMCOM ASC. The BRITE is a two-dimensional array of resistive elements that emit selectively across the entire MWIR and LWIR spectrum. The individual elements are thin film silicon nitride membranes over CMOS drive electronics arranged in 512x512 format. The array has a pixel pitch of 50um and the emitters have a temporal response of approximately 5 milliseconds. The complete projector system also includes drive electronics, cooling sub-system, system control computer, and a scene generation computer which renders the 2-D scenes from a 3-D database at a frame rate of 60Hz.

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1.3 Physical Layout

Both wavebands will simultaneously be used to stimulate the common aperture of a unit-under-test (UUT) that is normally mounted in a flight motion simulator (FMS) providing the necessary degrees of freedom to emulate missile flight dynamics. The beam combiner makes it possible for both sources to be coincident along the UUT viewing axis. The dichroic beam combiner is located in the anechoic chamber and reflects the IR scene while transmitting MMW signals.

A target array of antennae generates the MMW radiation included in this simulation arrangement. It is located approximately 33 feet from the beam splitter in an anechoic chamber measuring 28 x 34 x 34 feet (Figure1).

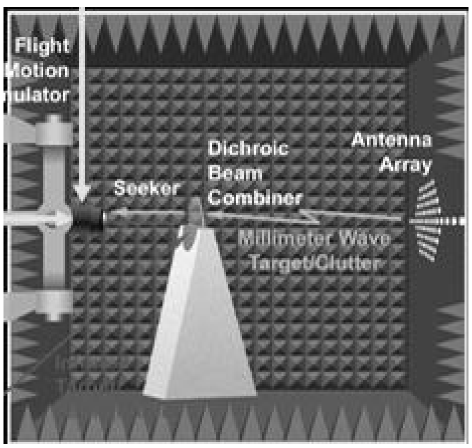

Figure 1. Chamber Schematic

Figure 2. Dichroic Beam Combiner

The combining element itself is an optically flat 27 inch diameter fused quartz window with a dielectric MWIR reflecting coating on one side (Figure 2). The beamcombiner serves as a fold mirror in the collimated IR projected beam. It is located 48 inches in front of the FMS with the geometric center aligned with the boresight of the UUT and the normal to its surface bisecting the angle between the projector optical axis and the boresight of the UUT. This axis is located at a height of 13 feet from the chamber floor. The IR projector is located in the adjacent laboratory along with the flight table. There are thus two portals between the two rooms. One opening is so the collimated IR radiation may be transmitted to the dichroic, where it is combined with the MMW radiation. The second opening is so that the combined beams may transmit from the splitting element to the entrance pupil of the UUT.

1.4 Purpose

The focus of this paper is to detail the design of the IR collimator given the geometric constraints and optical specifications of this facility, to analyze the resulting performance, and to present sample imagery taken from a UUT looking at an IR scene projector using this collimator. The goal of this design was not only to project IR scenes of acceptable image quality, but also to minimize cost, and ensure alignment with the other waveband by over-sizing the pupil and allowing a slight focal length variation.

2.0 DESIGN CONSTRAINTS

2.1 Array

The BRITE array is fabricated by Honeywell Technology Center and consists of a mosaic array of thermal emitters exhibiting excellent uniformity and resolution. The array, contained within a vacuum enclosure and located 5mm behind a 5mm thick AR coated ZnSe window, emits over the entire MW and LWIR spectrum. However, the projector is currently only required to cover the MWIR band from 3 to 5 um. Hence the requirement imposed upon the collimator is that it is only

optimized in the MWIR. For mechanical and precautionary reasons, a minimum working distance of at least 2 inches is desired between the window and the optical assembly.

2.2 Collimator

It is necessary that the location of the IR projector does not influence or disrupt in any way the characteristic signature of the MMW beam. Thus, the beam combiner is rotated to some angle relative to the MMW line of sight and the mechanical constraint driving the design becomes the large pupil standoff. The energy generated by the emitter array was required to be collimated, incident upon the optically flat beam combiner at an angle of 22.5 degrees mechanical, and reflected, filling a pupil that is coincident with that of a dual band- sensing seeker. The dichroic element, located in the adjacent MMW chamber, is displaced 48 inches from the flight motion simulator (FMS). Hence, due to this distance and the required angle of incidence, the optical assembly must be a minimum of 116 inches from the entrance pupil. Table 1 summarizes the design constraints.

PARAMETER	SPECIFICATION
Effective Focal Length	598 mm ±10%
Entrance Pupil Relief	2943 mm
Entrance Pupil Diameter	100 mm
Back Focal Length	>50 mm
FOV/ Image Area	40 mm Diameter Circle
Spectral Band	3- 5μm
Point Spread Function	<51μm RMS diameter
Distortion	<0.2%
Pupil Uniformity	>98%
Relative Illumination	>99%
Environment	20- 50°C

Table 1. Design Constraints

After oversizing the pupil diameter twofold to ease alignment difficulties, the minimum optical diameter of the lead element exceeds 11inches. As a result, to reduce the cost of fabrication, materials, tooling, and assembly, the design was to be based upon a format that includes only one large element (12inch diameter) and several smaller elements. The collimator assembly and balance of the projector was to be mounted upon a standard optics table with ¼- 20 tapped holes on 1 inch centers.

Several alternatives were considered and dismissed due either to cost or performance. Among those considered were a single binary element, an off- axis catadioptric system, and two 12 inch refractive elements.

3.0 COLLIMATOR DESIGN

3.1 Physical Description

The final system (Figure 3) is a single assembly containing four spherical refractive elements designed by Optical Sciences Corporation and fabricated by Janos Technology. Three of the lenses, including the 12 inches diameter lens, are made of silicon, while the fourth and only element of negative power is comprised of germanium (see Figure 4). All lenses are AR coated for 3- 5um. The housing is a tapered tube style while the support structure is a plate extending the length of the assembly for direct mating to a standard optics table. The material is ¼inch black anodized aluminum. The housing also includes a rotating section that may be easily threaded (via brass knobs) for adjustment of the focus.

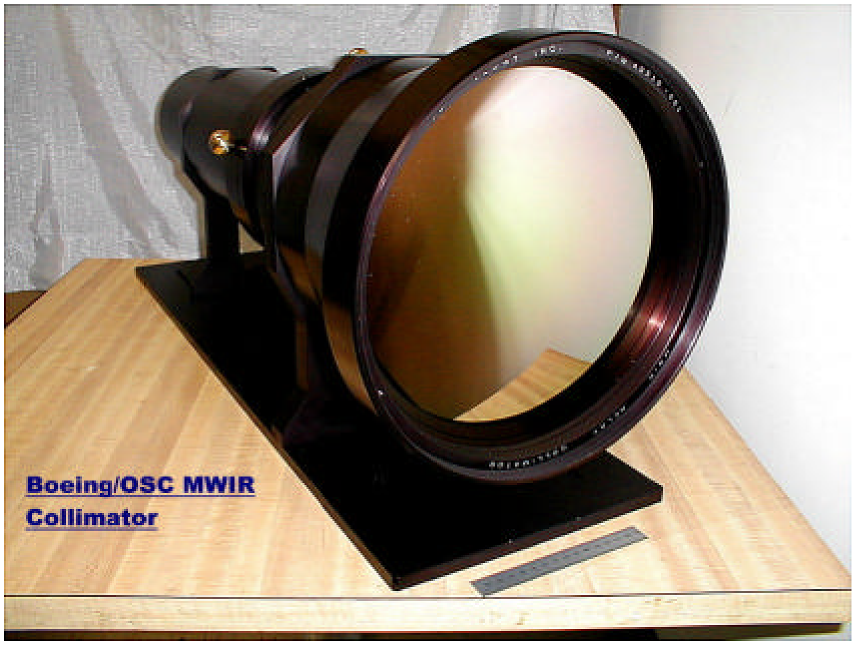

Figure 3. Collimator

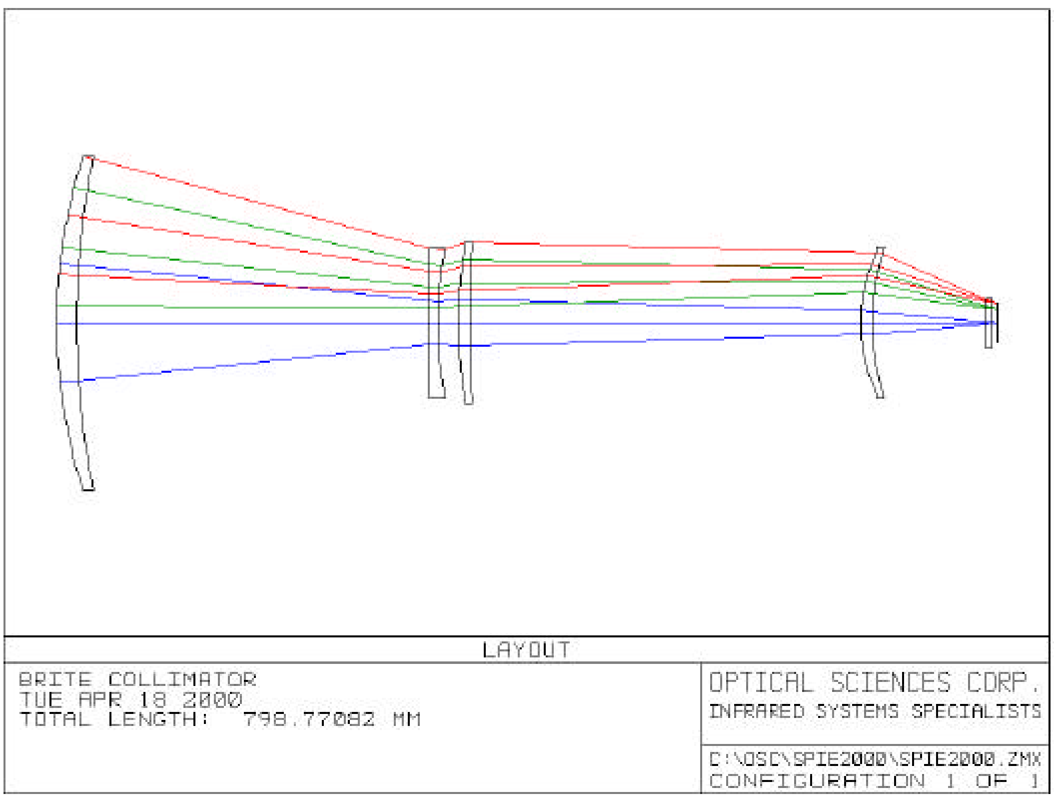

Figure 4. Detailed Ray Trace

3.2 Ray Trace

The large pupil relief of this F/5.4 system is somewhat of a departure from typical infrared scene collimators. Typical HWIL standoff distances between the last lens surface and the pupil of the system are on the order of 18 inches. For this application, the standoff must be 116 inches (Figure 5). The figure shows the surface representing the dichroic beam splitter and the three field points for the on- axis and the 1.77° circular field.

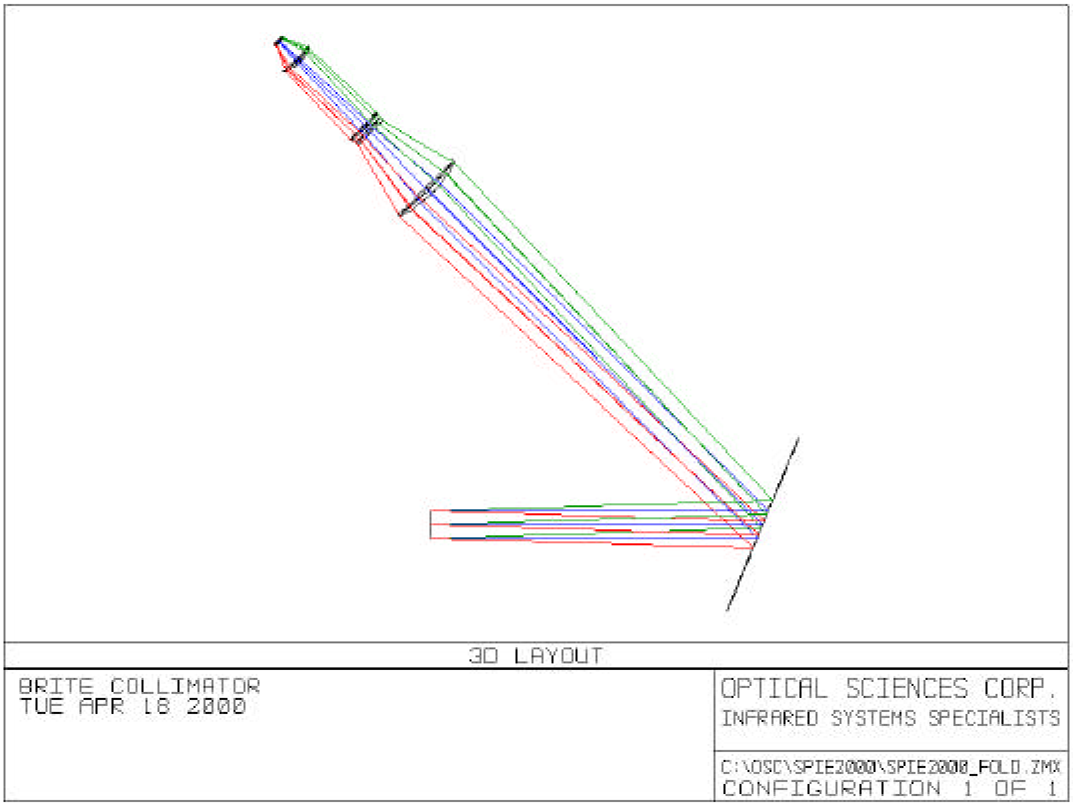

Figure 5. Ray Trace From Image to Pupil

The total fold due to the reflection at the beam splitter is 45° optical. The length of the collimator from first surface to last is approximately 34inches. The silicon-germanium combination, which is located nearly midway between the outer two elements, may be translated in tandem to allow for a modest focal length variation of ±10%.

3.3 Performance

This design was optimized using standard optical design software. Along with ray fan plots (Figure 6), data indicating point spread functions (Figure 7), focal shift as a function of wavelength (Figure 8), and a distortion grid (Figure 9) are included for reference.

Inspection of the transverse ray fans and other plots reveals the types of aberrations present in the system. There exists a negligible amount of spherical and coma while the system suffers slightly from astigmatism. The most pressing imaging errors here are chromatic to some degree and distortion, evident by the off- axis location of ray pierce as the field is heightened.

The axial and lateral chromatic aberrations are optimized for the center wavelength (4µm). The maximum variation in the focal length is from this value to the shortest wavelength (3µm). Here, the delta is 103µm while 160.2µm is the overall shift. Thus, the figure of merit for this system is the value implied by the diffraction limit, or ±235µm, which is represented as the largest value on the plot.

As for the other considerable aberration, distortion, 0.2% would represent a warping of one pixel out of 500 in the image plane. For the extreme field point, or the corner of the array, this collimator suffers from barrel distortion of magnitude 0.2028%.

The geometric blur spots for three field points representing the on- axis case, horizontal/ vertical, and corner of the array are shown. For a reference, they are drawn within a box with a side measuring 50µm, the size of one array pixel projected to the infinite conjugate. Additionally, the Airy disk diameter for this system is 53µm. Thus, overall optical performance over the entire 3.5° field of view exceeds that imposed by diffraction effects.

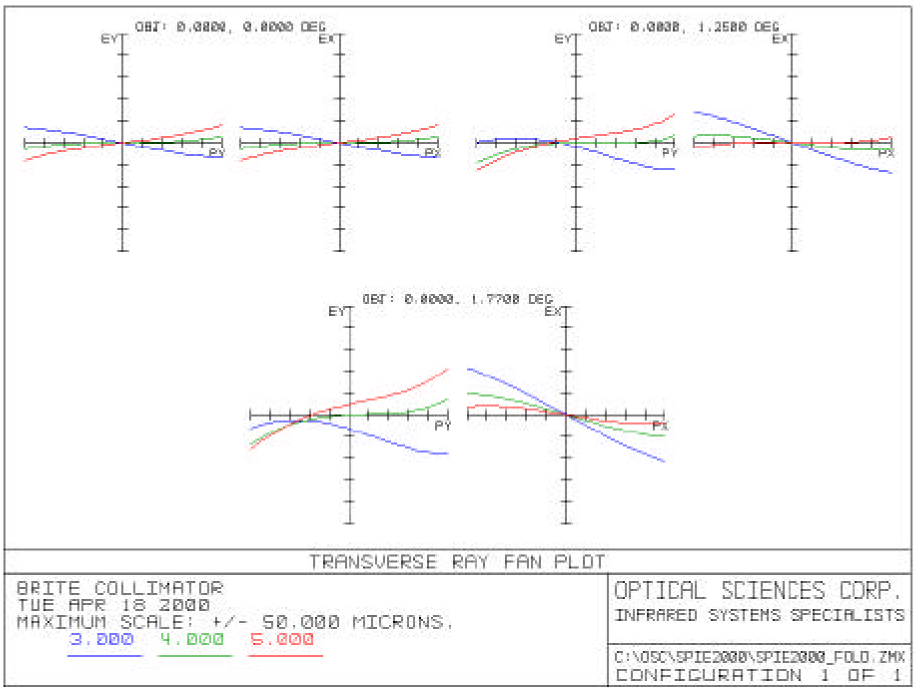

Figure 6. Ray Fans

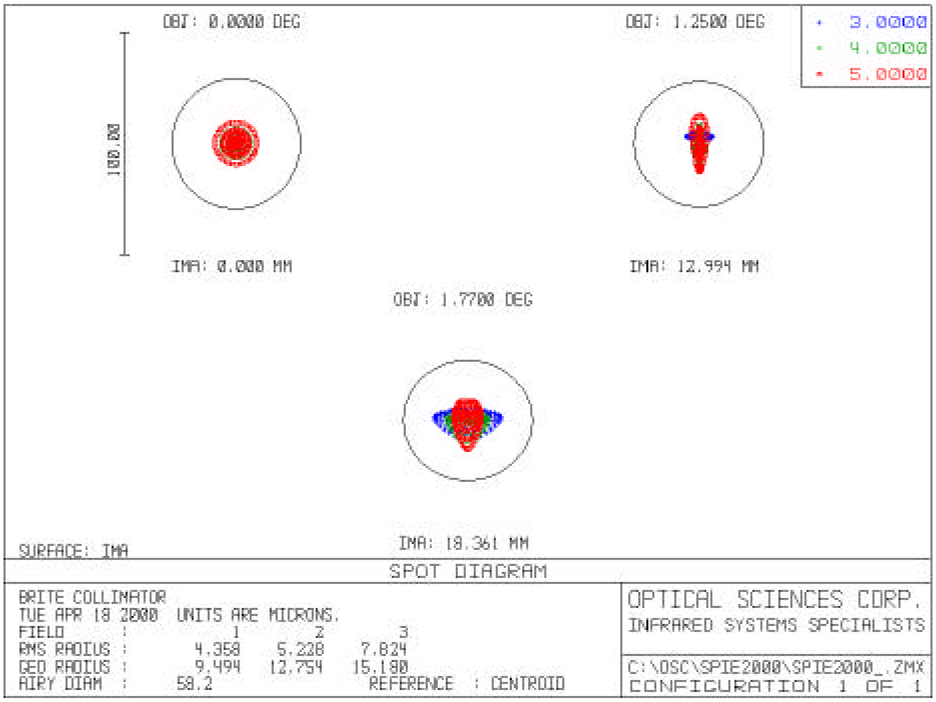

Figure 7. Spot Diagrams

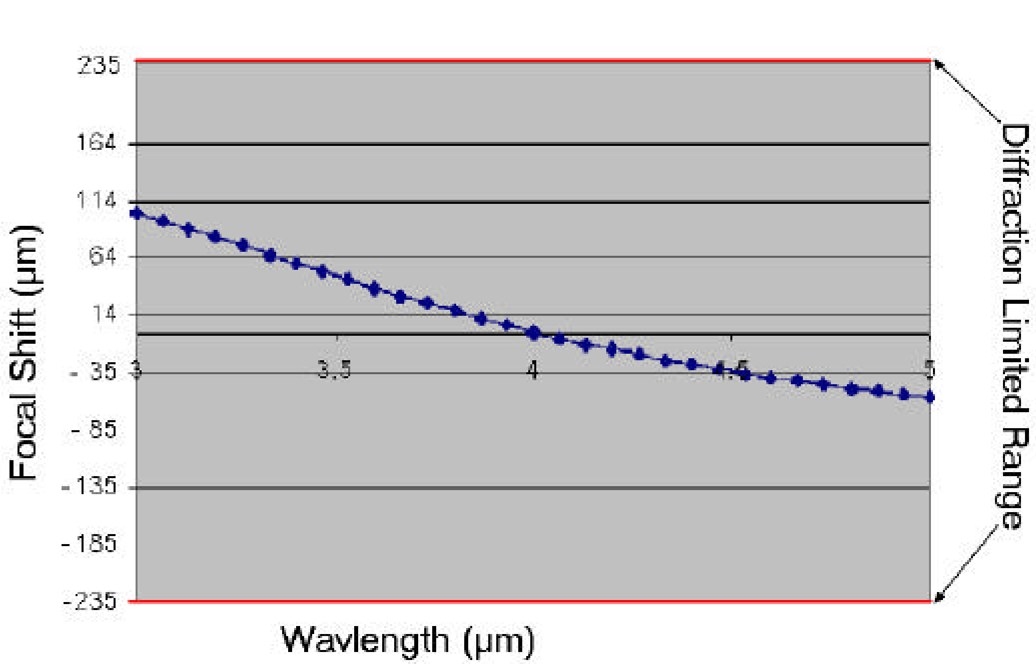

Figure 8. Axial Chromatic Focal Shift

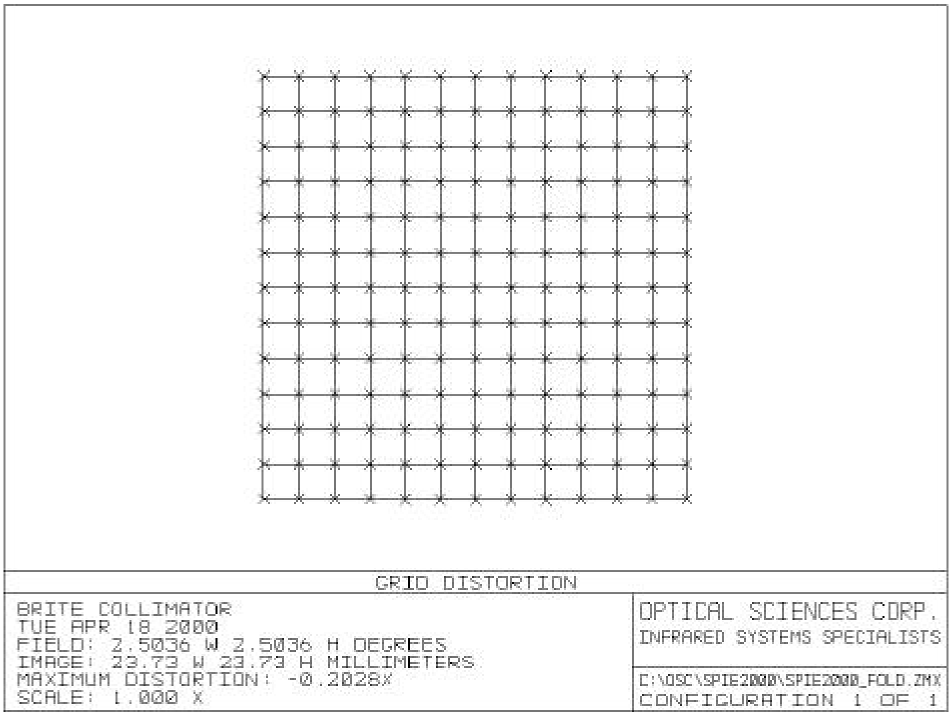

Figure 9. Grid Distortion at Full Field

4.0 TESTING AND ANALYSIS

HWIL simulations have been performed with the projector system including the BRITE array and collimator. Sample images are presented to demonstrate resolution and dynamic range of the projection system. Transmission losses were also measured for the optical collimator.

4.1 Sample Imagery

Figures 10 and 11 were projected using the BRITE system and the collimator. The images were collected by a 256x256 MWIR sensor. The former is a bitmap image of a trailer containing a broadband source while the latter is a picture of a sample HWIL target. These images demonstrate the good resolution, contrast, and dynamic range of the projector at the nominal pupil relief of 116 inches.

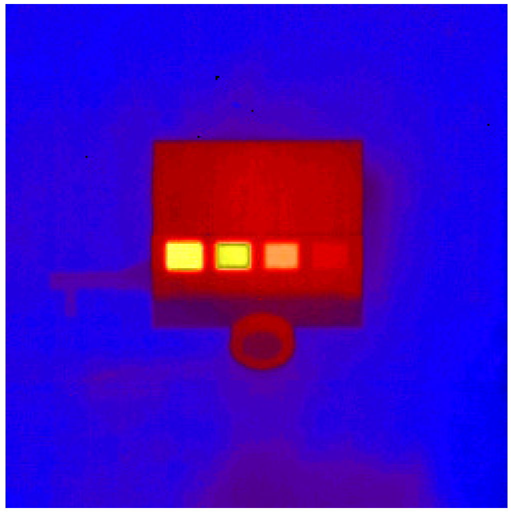

Figure 10. Blackbody Trailer

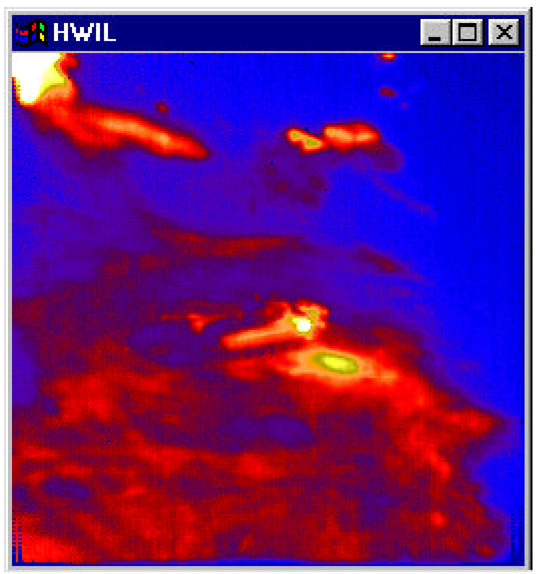

Figure 11. HWIL Target

4.2 Transmission Measurements

Transmission data were taken using a standard blackbody source and the MWIR camera with the 2.5° lens. First, the camera is focused upon the source and mean number of counts produced recorded for two different temperatures. The measurement is then repeated with the collimator providing the focus upon the source and the camera focused at infinity. These data reveal an overall transmission through the system of 82%. This is as expected for four AR coated elements, each exhibiting approximately 96% average transmission individually.

5.0 CONCLUSION

The task of projecting MWIR dynamic scenes in a dual-band environment has been accomplished. The demand of maintaining alignment, filling the pupil, and preserving overall optical quality of the projected IR target/ background has been successfully negotiated using an optical collimator that provided the necessary 10 foot pupil standoff. The design was also optimized to minimize the cost of the system.

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